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**Final Report**

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Models and Mechanisms For Enhanced Sensory-Motor Control.

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## Contents



## I. Objectives

The overall objective of the project is to develop quantitative models of human spatial orientation which can help the Air Force enhance missions involving accelerative environments. Our specific experimental and modeling objectives build upon our recently published model of static spatial orientation. The three-year objectives are:

1. Determine whether there is cross talk between axes during static body tilt on the three primary axes using a multi-axis indicator of the vertical
2. Measure the subjective vertical during static body tilts involving displacements about several axes simultaneously
3. Test whether velocity integration of position fails in 0g, and determine whether it is augmented in 1.8g re 1g
4. Determine whether somatosensory stimulation can be used a) to provide spatial reference cueing in 0g to restore path integration, and b) to provide accurate perceived spatial displacement in 1.8g during CCCS.

Potential products of relevance to the Air Force are:

1. Predictive models of orientation errors
2. Techniques for sensory enhancement of human performance
3. Evaluation of human-machine interactions
4. Evaluation adaptation to human-machine interactions and re-adaptation to normal conditions

## II. Status of effort

In the past year we have been collecting data with our rotating room, a rotating chair equipped for sensory localization experiments, our multi-axis tilt device. Two weeks of experimentation have been conducted in parabolic flight aboard NASA's C-9 aircraft.

1. Our new, unique, multi-axis tilt device purchased with funds from a previous DURIP grant is fully operational, and it has been used to collect data on the ground and during parabolic flight missions in NASA's C-9 aircraft.
2. The multi-axis device enables the study of 3-dimensional orientation. A major effort for this year was developing mathematical techniques for representing 3-dimensional data (quaternions), presenting results in an intuitive manner (cardinal axis projections), and for calibrating measurements. All of these technical achievements are novel in the field of human spatial orientation.
3. We have collected the first complete, comprehensive assessment of human three dimensional estimates of the subjective vertical in 1 g on the ground and in 0 g and in 1.8 g, in parabolic flight
4. We have evaluated perception of body angular displacement under conditions where subjects had to rely upon the integration of information about angular velocity.
5. We have evaluated the effects of linear acceleration on the localization of visual, auditory and vibrotactile stimuli.
6. We have evaluated the effects of angular acceleration on the localization of visual and auditory stimuli.

## III. Accomplishments

1. Measurement. A major technical challenge which was overcome this year was development of an accurate system for measuring human spatial orientation in 3 dimensions. In our experiments, we use a multi-axis tilt device to position subjects in any desired 3 dimensional orientation, and we ask them to indicate the direction of "up" by holding an indicator stick aligned with the vertical direction. In such experiments, the system for measuring stick orientations must be an more accurate than human responses, under the following conditions:

- It must provide orientation measurement in 3 dimensions.
- It must operate over the 360° range of possible stick orientations.
- The measurement device itself must not introduce cues which would contaminate "vertical" judgments.
- It must operate within the environment of our multi-axis tilt device

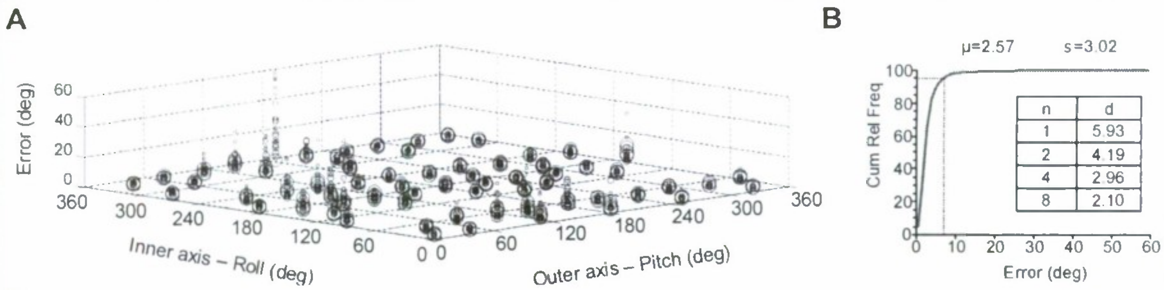
A mechanical system with nested gimbals prohibits continuous 360° operation, and the cantilever arm which would be required to support any such system relative to the tilting subject chair would provide a tactile/haptic alternative framework which could interfere with vertical judgments. The use of optical systems for tracking stick motion is prohibited by occlusions from structural parts of the tilt device as well as the subject's arms. Ultrasonic acoustic systems are somewhat less prone to occlusion, but are rendered unusable by even minor stray noise from the motors of the tilt device or the simple sound of a subject or operator clearing their throat. Devices based on integration of miniature rate gyro signals would be confused by the non-inertial framework of the rotating tilt device itself and also by the unusual gravitoinertial acceleration backgrounds (parabolic flight, rotating room) in which the tilt device must be used for the proposed experiments.

We chose to use a device (the Polhemus FASTRAK) which is based on the principle that the 6 degree of freedom position/orientation of a search coil can be determined within a known AC magnetic field. Such devices have none of the shortcomings of the systems mentioned above. However, a remaining problem is that any magnetic field generated within the volume we need to track is highly distorted by the surrounding metallic parts of the tilt device, thereby distorting the sensed position/orientation of the search coil. Moreover, in our experimental situation, the distortion is not constant because the field-producing coil is fixed to the inner gimbal arm of our tilt device which moves in relation to the metallic outer gimbal arm and its base. Thus, the measured orientation of the search coil depends on the spatial orientation of the entire subject within the tilt device and of where the subject holds the indicator stick (with the sensor attached) within the tracking volume, which is fixed relative to the subject restraint chair. Our solution involved i) devising an efficient method for collecting adequate calibration data for mapping the distortion of the magnetic field within the experimental tracking volume over the entire sphere of possible chair orientations and ii) generalizing to 6 degrees of freedom a published algorithm (Zachmann, 1997) for calibrating only the three translational degrees of freedom.

A calibration jig was constructed which could hold search coils at 80 locations within a 15 cm wide x 15 cm high x 20 deep tracking volume, at 5 cm intervals along each dimension. The calibration jig can be fixed relative to the laboratory floor at the location where the two axes of the multi-axis tilt device intersect. When fixed at this location, the calibration jig volume encompassed the area where a group of pilot subjects were comfortable holding the indicator stick while performing subjective vertical judgments. A calibration data collection program was written which acquires data from sensors at every location while the tilt device (to which the field coil is affixed) is moved to a sequence of 65 different orientations on a sphere around the calibration jig. The chair accurately acquires the programmed orientations to within and accuracy of better than 1 arc minute. The program can collect data from four sensors simultaneously (the maximum permitted by our equipment), and within 1 hour we can collect a data set of 65 known sensor orientations x 80 sensor loci in the tracking volume x 8 repetitions. This makes calibration feasible when the device is moved to different environments (parabolic flight, rotating room).

To verify the calibration algorithm, we also collected a second data set in which the entire calibration jig was moved 2.5 cm on both the anterior-posterior axis and the medial-lateral axis. In addition, the tilt device orientations used were shifted by 10 degrees in both component axes. These translational and rotational displacements produced a unique verification data set. However, some sensor positions were displaced outside the calibrated volume. Thus, the verification set contains 65 orientations x 36 sensor loci x 8 repetitions.

The calibration algorithm interpolates field distortion between the measured calibration positions and corrects for these distortions. It uses a radial basis function on a 7-dimensional space. On the input side of the interpolation, three dimensions represent the raw (distorted) sensor position read from the magnetic tracking system. The four remaining dimensions represent the orientation of the tilt device in the form of a unit quaternion. On the output side of the interpolation, three dimensions represent the actual sensor position and the four remaining dimensions represent the orientation



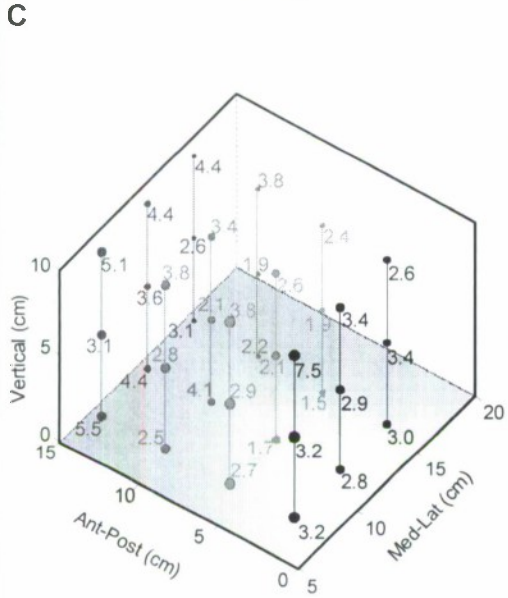




**Figure 1**. Calibration of the Fastrak device was carried out by measuring each of 65 pitch-roll orientations (covering the full 360° range in both axes) of sensors at 80 loci within a tracking volume 15 cm wide x 15 cm high x 20 deep. This set of 8 repetitions of 65x80 measurements was used to identify calibration coefficients, and a second set of 8 repetitions of 65x36 measurements was collected at slightly different locations to verify the calibration process.

**A**. Measurement errors of the verification data set. Error magnitude is the average over repetitions of the absolute value of the three dimensional resultant angular deviation between the measured and true orientations of the sensor. The size of the dots is inversely proportional to the Euclidean distance of the stick from the centroid of the tracking volume. There is no evidence of systematic variation in error as a function of orientation. The errors are quite small except for one orientation, at the edge of the calibrated volume.

**B**. Cumulative histogram of error magnitudes shown in panel A. The inset table shows the magnitude of measurement error we can expect with 95% confidence (d) as a function of the number of experimental repetitions we make of each measurement (n).

**C**. The average measurement error over orientations and repetitions is uniform except at the boundaries of the tracking volume.

displacement between any raw (distorted) sensor orientation and the corresponding actual sensor orientation for the given combination of sensor position and tilt device orientation. The orientation output is normalized to a unit quaternion. Precedent for using radial basis functions for interpolation of spherical data is found in (Fasshauer, 1998).

Verification of the calibration algorithm was carried out by analyzing the three dimensional angular resultant errors (pitch, yaw and roll) between the known orientations of the verification data set and the output orientations produced by the calibration procedure. Figure 1 presents the error the errors for all 65 sensor angular orientations, with each blue symbol representing one of the 36 sensor locations within the translational coordinates of the calibration volume (smaller symbols are farther from the center of the volume). The flat plane formed by the error values shown in Figure 1A indicates that the differences between actual and measured orientation are uniform over the entire sphere surrounding the calibration volume. The dispersion of the smaller dots in Figure 1A shows that just a few orientations show low accuracy when the sensor is positioned at edge of the calibrated volume. Figure 1B shows a cumulative histogram of the errors. The 95% confidence interval of this population of measurement errors is

5.93°. This represents our angular measurement resolution for a single experimental measurement. The inset table in Figure 2B shows that by collecting multiple experimental measurements in a given condition we can achieve resolutions down to ~2°. The 95% confidence interval of typical subjects' ability to indicate the subjective vertical with an indicator stick is ~8°. Figure 1C labels the errors, averaged across all 65 sensor orientations at all 36 locations in the calibration volume. The data show that the errors do not change systematically throughout the calibration volume. We expect that this resolution can be improved by collecting calibration data with smaller increments of orientation.

Efforts are currently underway to use this calibration technique to process data we have collected on the ground and in parabolic flight using the mulit-axis tilt device. We estimate that one manuscript will be submitted by December describing the ground-based results and a second manuscript will be submitted by January describing the parabolic flight results.

Air Force Relevance: We will publish a paper on this technique, because magnetic tracking systems, Polhemus devices in particular, are commonly used in research on spatial orientation and control of posture and movement. In addition, they are common components of many virtual environment applications, such as head tracking for visual update of helmet mounted displays. Our calibration algorithm/protocol can improve the performance of Air Force relevant virtual environment applications which incorporate head tracking and must operate in environments which would distort magnetic fields. For example, accurate head tracking is critical for high fidelity flight simulations as well as for spatially accurate overlay of head's up display information onto see-through scenery.

2. Angular path integration in variable acceleration backgrounds. We have completed the analysis of a preliminary report on angular path integration which we submitted last year, and a manuscript is currently under review (Appendix A.1). The goal of these studies was to determine whether velocity-to-position integration of semi-circular canal signals is altered in non-1 g linear acceleration environments. This question is critical for expanding our static spatial orientation model to cover dynamic situations in vehicles relevant to the Air Force.

We measured subjects' ability to indicate the amplitude of brief, passive tilts about their recumbent yaw axis. Tests were carried out in parabolic flight where background acceleration level varied from 0 to 1.8 g. Blindfolded recumbent subjects (n=7) were tilted about their horizontal z-axis 30°, 60° and 120° in amplitude leftward or rightward from varied starting positions. Tilts were manually executed and were less than ~1.5 sec in duration and at rates well above semicircular canal thresholds. The subject's task was to align a gravity-neutral pointer with the subjective vertical while in the static initial position and to keep it aligned with the vertical throughout the subsequent displacement. The specific instructions for aligning the pointer were to "use gravity as a reference when it is available, and imagine a constant spatial location in microgravity". In 0 g, subjects always felt supine and maintained the pointer perpendicular to their chest even while being tilted through amplitudes of 120°. In 0 g and 1.8 g, subjects counterrotated the pointer during tilts to maintain it in a nearly constant spatial direction. Subjective reports greatly underestimated self-displacement

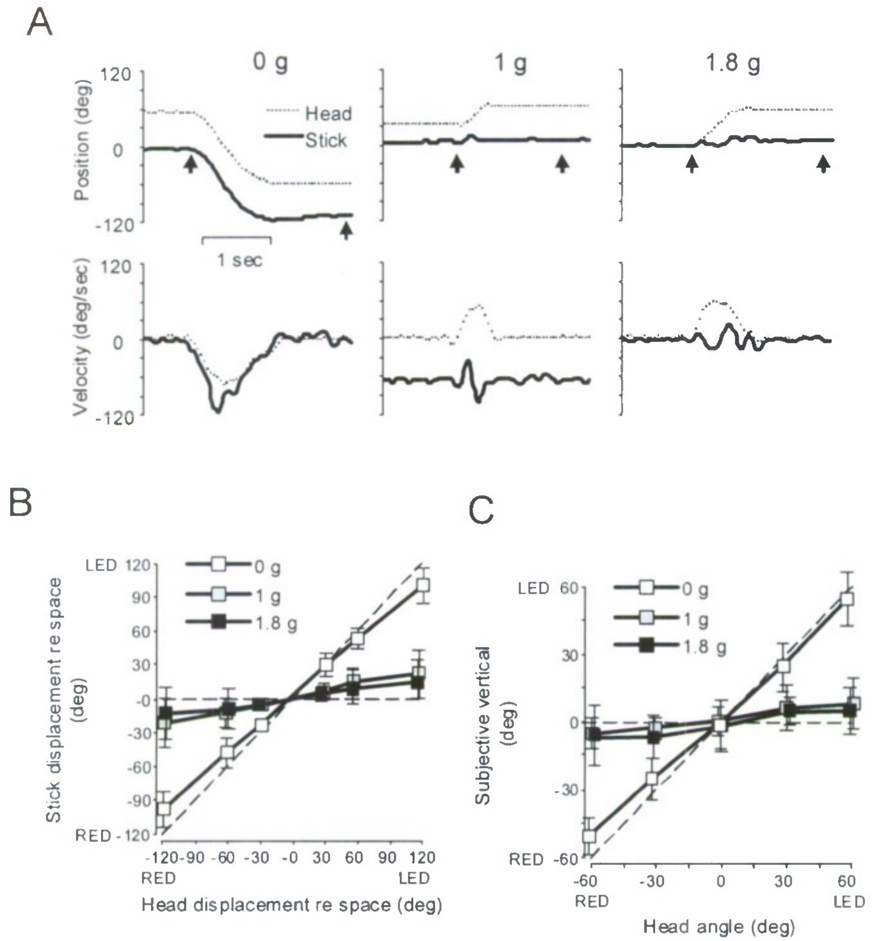



**Figure 2.** **A**. Time series of head (dotted traces) and joystick (solid traces) rotation relative to space during typical trials in different acceleration backgrounds. The arrows mark the points where initial and final head and stick positions were measured to compute displacements. Trials with different tilt amplitudes, directions and positional ranges are illustrated. **B**. Plot of final stick displacement versus recumbent yaw axis head displacement. Subjects were attempting to continuously align the stick with the subjective vertical in the different acceleration backgrounds. The horizontal dashed line indicates a constant orientation of the stick to the spatial vertical and the

in 0 g and estimated it accurately in 1.8 g and 1 g. The 0 g attenuation of spatial updating suggests either that velocity-to-position integration of semicircular canal signals is attenuated by graviceptive unloading or that unchanging, evenly distributed somatosensory pressure cues in 0 g lead to a constant haptically derived "vertical" which overrides the sense of displacement normally derived from integration of canal signals.

Air Force Relevance: Aerobatic environments include fluctuations in linear acceleration magnitude as well as angular accelerations. Building a model which can predict human performance in such environments requires a model of sensory and CNS interactions in processing of linear and angular acceleration.

3. Multisensory localization. We have performed two new experiments utilizing our new data and model of static spatial orientation (Bortolami et al. 2006; Bryan et al. 2007) to assess sensory localization during linear acceleration.

3.a. Reference frame for sensory localization during linear acceleration. We have submitted a manuscript (Appendix A.2) describing the effects of linear acceleration on the ability of subjects to localize auditory and visual targets. We chose to examine localization in the azimuthal plane of the head because auditory and visual localization are ordinarily quite precise in this plane when the targets are close to straight ahead. In addition, our previous data and modeling work (Bortolami et al. 2006; Bryan et al. 2007) indicated that the magnitude of linear acceleration does not affect the subjects' subjective vertical during recumbent yaw axis (azimuthal plane) tilts, allowing us to evaluate the direct effects of linear acceleration on target localization, uncontaminated by orientation errors. By studying both visual and auditory localization, we aimed to discriminate effects of linear acceleration on multisensory frames of reference, which

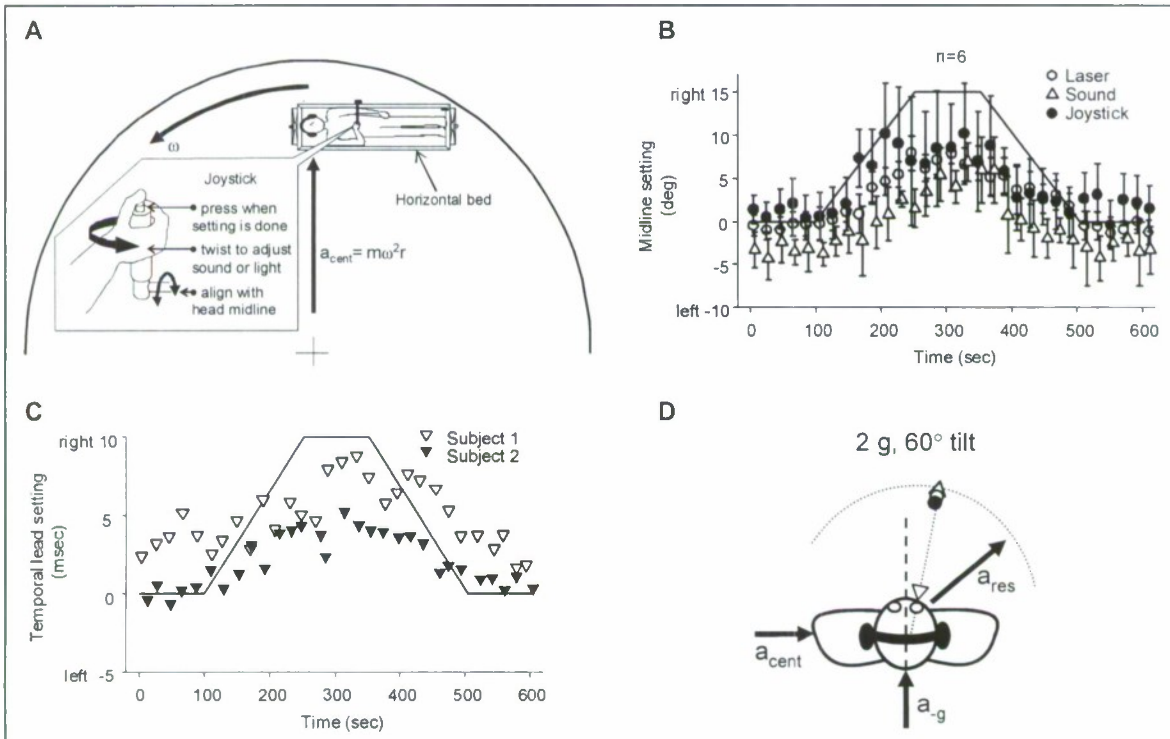



**Figure 3**. **A**. Illustration of the experimental situation and joystick used to adjust visual, auditory, and somatosensory stimuli and to indicate head midline. ω = the angular velocity of the rotating room, $a_{cent}$= centripetal acceleration, r= radius, m=mass. **B.** Plots of the average settings and standard deviations of auditory (Δ), visual (○), and haptic (•)head midline settings and ω (normalized) as a function of time, across subjects and experimental runs. **C**. Plots of the settings of the time lead of a tactor on the right side of the forehead with respect to the left side which created a feeling of one fused stimulus in the head midline. **D**. Schematics of auditory, visual, haptic and vibrotactile settings made when the gravitoinertial resultant acceleration magnitude is 2 g and its direction is tilted 60° relative to the midline (dashed line). We propose that all settings are made in relation to an extra-corporeal frame of reference (dotted arc and reference line) which shifts in the direction of the gravitoinertial resultant's rotation by a fraction of the angle of rotation.

would cause common effects on visual and auditory localization, from effects of acceleration on the oculomotor system, which would preferentially affect vision.

Individuals exposed to both an increase in magnitude and rotation of the gravitoinertial acceleration vector experience changes in visual and auditory localization and apparent body orientation. These effects are known as the oculogravic, audiogravic and somatogravic illusions, respectively (Clark and Graybiel 1949; Graybiel 1952). We measured the magnitude, direction, and time course of the audiogravic and oculogravic illusions in recumbent subjects ($n$=6) exposed repeatedly to a 60° azimuthal rotation of the gravitoinertial acceleration vector and an increase of its magnitude to 2 g, in the Brandeis slow rotation room (see Figure 3A). Before, during and after rotation, subjects were asked to adjust a visual target or an auditory source to their head midline. Subjects also used a pointer to haptically localize their subjective head midline. Parallel, time linked changes in auditory, visual, and haptic localization of comparable magnitude and direction occurred (see Figure 3B). Two additional subjects adjusted the onset asynchrony of a pair of pulsing tactors on the forehead until they experienced a fused, midline sensation. A vibrotactile shift occurred during exposure to altered gravitoinertial acceleration in the same direction as the auditory, visual, and haptic shifts (see Figure 3C). These parallel multimodal results point to a gravitoinertial acceleration induced remapping of a peri-personal spatial referent underlying the changes in localization of auditory, visual, and somatosensory stimuli (see Figure 3D). Vestibular, somatosensory or oculomotor signals could be responsible for the proposed shift in the external reference system.

Air Force Relevance: This study indicates that exposure to a dynamic linear acceleration will alter multisensory target localization and target pointing. The shifts in auditory and tactile localization are important because synthetic auditory and vibrotactile displays are being considered as alternative displays to relieve perceptual/cognitive load on the visual system or to circumvent common visual spatial illusions induced by exposure to acceleration. Our results indicate there will be errors in alternative display localization as well. We predict that multi-modal targets will show shifts as large as those of the uni-modal targets we used here, because all individual modalities showed parallel shifts. However, these errors will be systematic and can be calibrated for, with sufficient knowledge of their psychophysics.

3.b. Adequate linear acceleration stimulus. The experiments described in the previous section prove that sensory localization relative to the head midline is altered by a directional change relative to the midline of a 2 g resultant acceleration vector. Our previous experiment on the audiogravic illusion (DiZio et al. 2001) showed that an increase from 1 g to 2 g of the resultant acceleration without a change in its direction does not alter localization and that a change in direction of the normal 1 g acceleration (e.i., body tilt) causes a small but statistically reliable shift in localization. This section describes experiments performed to determine whether the directional change of a hyper-g resultant acceleration or the non-gravitational component of that resultant is responsible for the previously observed acceleration-induced localization shifts relative to the head midline.

First, we repeated the previous experiments in which subjects lay supine with their head pointing in the direction of room rotation (see Figure 4A). This generated a

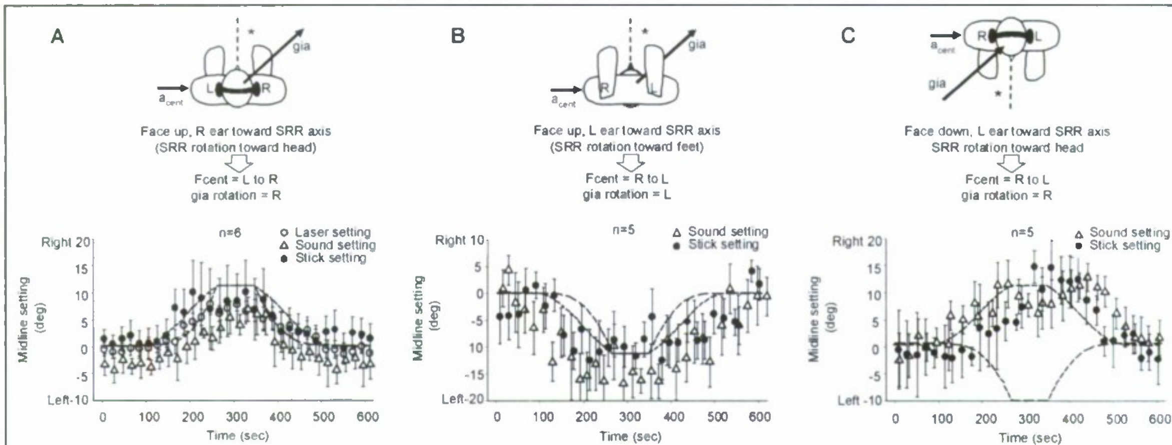



**Figure 4**. Illustration of three conditions in which the resultant acceleration and component accelerations on the body in the rotating room are manipulated. Arrows In the schematic diagrams at the top represent the accelerations associated with contact forces on the body: centripetal acceleration ($a_{cent}$) and the resultant (gia) of $a_{cent}$ plus the acceleration opposing free fall due to gravity. The asterisk indicates where subjects set auditory and visual targets to appear on the head midline. In the midline setting plots at the bottom, the direction of gia (short dashed lines) and the direction and magnitude of $a_{cent}$ (long dashed lines) are plotted along with visual and auditory midline settings as a function of time. **A**. $a_{cent}$ directed rightward and gia rotates rightward (clockwise), and midline setting shift rightward. **B**. The body is rotated 180° in the floor plane of the rotating room relative to A, so that $a_{cent}$ (leftward)and gia rotation (leftward, counterclockwise) both reverse, and localization reverses. **C**. Body rotated around it long axis relative to A, so that $a_{cent}$ reverses (leftward) relative to A but gia rotation (rightward, clockwise) is the same as in A, and the localization errors are the same as in A.

centripetal acceleration from left to right along their inter-aural axis and a rightward angular excursion of the resultant of centripetal and gravitational accelerations. The visual and auditory midline settings shifted rightward, replicating the previous findings. Next, we positioned the supine subjects with their feet leading. In this situation, the centripetal acceleration was leftward, the resultant acceleration rotated leftward, and the auditory and visual midline settings shifted leftward (see Figure 4B), which is also consistent with our previous finding. Finally, we positioned the subjects prone instead of supine, with their head in the direction of rotation (see Figure 4C). This created a situation where the centripetal acceleration was leftward but the resultant rotated rightward, and the midline settings shifted rightward (see Figure 4C). These results indicated that multisensory localization shifts are driven by rotations of the resultant acceleration rather than by the direction of the non-gravitational component of the resultant. When the gia direction rotates clockwise, the localization of the midline shifts clockwise, subjects perceive counterclockwise self-rotation in space, and a stationary target appears to move counterclockwise relative to the head.

Air Force Relevance. This result is important because it indicates that models of sensory localization should use the gravitoinertial resultant rather than the component accelerations as their input. This is in agreement with the basic postulates of our static spatial orientation model, in which information about the component accelerations does not survive beyond the sensory periphery and only an estimate of the angle of the head relative to the vertical is propagated centrally. Our model does not generate an internal representation of the gravitoinertial vertical consisting of component accelerations, but instead it assumes a 1 g resultant and computes what head angle in a 1 g field would

have produced the sensed components. It appears that only the rotation of the resultant influences sensory localization, so the early stages of processing in of static spatial orientation model are suitable for predicting sensory localization as well.

3.c. Reference frame for sensory localization during angular acceleration. The studies of sensory localization described above are important due to two of the conditions used for testing - the use of multiple sensory modalities and the use of linear acceleration. These conditions permit new insights into mechanisms of sensory localization during angular acceleration, which is the topic of this section

Our use of linear acceleration is important, because it evokes very low gain reflexive eye movements, in contrast to angular acceleration which evokes a powerful nystagmus reflex. Involuntary eye movements must be suppressed in order to maintain fixation of visual targets one is trying to localize, and oculomotor suppression signals have been hypothesized to be the cause of the oculogyral illusion, a type of visual mislocalization error which occurs during angular acceleration (Graybiel and Hupp 1946; Whiteside et al. 1965). The absence of oculomotor factors in our linear acceleration experiments unmasked a new multi-sensory mislocalization mechanism – the acceleration dependence of an extra-corporeal reference frame. A second argument in support of this multi-sensory reference frame shift is that visual, auditory haptic and vibrotactile targets showed parallel shifts during linear acceleration. If oculomotor suppression signals were operative then the visual shifts would have differed from the non-visual ones.

This raises the question whether a similar multi-sensory reference frame shift contributes, along with oculomotor suppression signals, to sensory localization errors during angular acceleration. If non-visual targets as well as visual ones undergo head-relative apparent displacement during angular acceleration, it would support the angular acceleration dependence of a multi-sensory, extra-corporeal reference frame. As summarized at the end of the previous section, rotation of the resultant linear acceleration which evokes apparent self-motion will evoke the same direction of apparent head-relative motion of a head-fixed target. By extension, we conjecture that angular acceleration should evoke head-relative shifts of a stationary target in the same direction as that of apparent body rotation. Therefore, we predicted shifts would occur in haptic and auditory localization of the head midline in the same direction as body acceleration. We predicted visual shifts would occur in the same direction but they would be larger than non-visual shifts because additional oculomotor suppression signals would differentially contribute to visual localization.

We have completed a series of experiments in which subjects in a rotating chair set a visual target to appear straight ahead in their head midline or used a pointer to indicate their head midline. The room was dark except when the visual target was being used. Subjects performed this task while stationary, while accelerating at various angular rates for periods of 2 to 20 sec and while rotating at constant velocity for 60 sec. A head-fixed visual target appeared to move relative to the head in the direction of acceleration, and subjects setting the light to their head midline deviated it in the direction opposite to acceleration. The direction and magnitude of the deviations were consistent with previous reports about the oculogyral illusion. The haptic midline pointing responses were deviated in the same direction as the visual settings, but the

haptic shift was significantly smaller. This pattern held true for a broad range of acceleration rates. See Figure 5. These results indicate that haptic and visual localization shifts are generated by an angular acceleration induced change in a multisensory reference frame, and that visual localization is additionally influenced by reflexive oculomotor responses to angular acceleration.

Air Force Relevance: These results will help us to generalize our existing static spatial orientation model to predict multi-sensory localization during dynamic linear and angular acceleration.

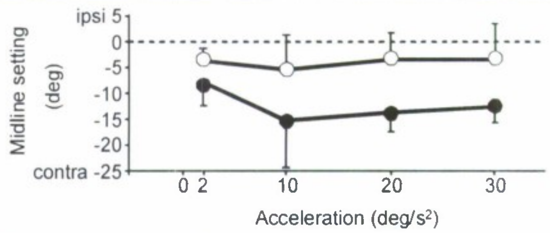



**Figure 5**. Plots of the magnitude of shifts in localization of the head midline by setting a visual target (○) and a pointer (●), as a function of angular acceleration rate. The data represent the peak magnitude of the shift which occurred after acceleration onset.

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**Personnel Supported**

James R. Lackner, PhD – Principal Investigator
Paul DiZio – Co-Investigator
Jerome Carriot, PhD – Post-doctoral student (6 months)
Avijit Bakshi – Graduate student
Mina Lehmann – Graduate student

**Publications**

Bryan AS, Bortolami SB, Ventura J, DiZio P, Lackner JR (2007) Influence of gravitoinertial acceleration level on the subjective vertical during recumbent yaw axis body tilt. Exp Brain Res. Appendix

DiZio P, Lackner JR (2008) Angular Path Integration Modulated by Graviceptive Signals. Exp Brain Res. Under review

Lackner JR, DiZio P (2008) Audiogravic and oculogravic illusions represent a unified spatial remapping. Exp Brain Res. Under review

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**Interactions**

AGILE Workshop. Drs. Lackner and DiZio were invited participants in a NASA Engineering and Safety Center (NESC) workshop on the Assessment of Gravito-Inertial Loads and Environments (AGILE) held October 10-12, 2007 at the Center for Advanced Space Studies (CASS) in Houston, Texas. The agenda of the meeting was to evaluate risks to future lunar missions due to the acceleration to which astronauts will be exposed.

TNO DESDEMONA Meeting. Dr DiZio was an invited speaker at the symposium on DESDEMONA held at TNO, Soesterburg, The Netherlands, December 10-14, 2007. The agenda for the meeting was to demonstrate the capabilities of the DESDEMONA multi-degree of freedom, linear/angular acceleration simulation device and to discuss possibilities for collaboration. There was the opportunity for personal discussions about spatial orientation models with important investigators such as Bos, Bles and van Gisbergen.

**Inventions**. None

**Honors/Awards** None